# Comparative Cost, Benefit, and Adoption Analysis of Color Filter on Encapsulation (COE) to Circular Polarizers (C-POL) in Anti-Reflective Film Applications for OLED Displays

**Charles A. Annis**
**Omdia, Kyoto, Japan**

## Abstract

**This paper compares the material costs, equipment depreciation, yield rates, and other costs that vary between COE and C-POL anti-reflective films. Additionally, it compares the benefits and challenges of adopting COE in place of C-POL. Based on these results COE adoption rates are forecast through 2030.**

## Author Keywords

OLED; COE; Circular Polarizer; Black PDL; brightness; power consumption; flexible displays; color gamut; photomasks; yield

## 1. Introduction

OLED displays reflect ambient light, most significantly from internal metal electrodes, causing glare, reducing contrast, and making them difficult to read, particularly outdoors.

Conventionally, circular polarizers (C-POL) have been applied to minimize reflection. Combining linear and circular polarization functions, C-POL converts ambient, linearly polarized light that enters the display into circularly polarized light and then converts light reflected from electrodes back into linear polarization again.

This reduces glare, but at the same time, the linear polarization also filters approximately half of the unpolarized OLED panel emissions, reducing brightness by about 50%.

There are a variety of C-POL solutions that range in cost and performance, including various combinations of positive and reverse wavelength, as well as film and LC types. The industry is now trending away from positive dispersion C-POL (POL + $\lambda/2$ + $\lambda/4$ retarders) and toward reverse dispersion type C-POL, either film-type or LC-type, owing to the simplified structure and enhanced performance.

LC-type C-POL have been preferred for foldable OLEDs because they are thinner and much more flexible than film-type. Additionally, LC-type C-POL provide better color reproduction.

Despite being more expensive, some flat bar type phones are starting to adopt LC-type C-POL because of the color enhancement and reduced thickness as well as because film-type C-POL may crack during the hole-punching process.

Even as C-POL technology has evolved, panel makers have developed COE as an alternative approach to reducing external reflection, further reducing panel thickness, maximizing flexibility, and increasing panel brightness.

COE offers a variety of advantages compared to C-POL, but not without trade-offs. Smartphone makers need to evaluate these trade-offs in detail when deciding what anti-reflection solution to choose. When doing so it is essential to know which is more expensive.

COE is a photolithographic process. Adding equipment to fabricate COE onto OLED panels requires substantial capital outlays and drives other additional manufacturing costs. At the same time, expensive add-on C-POL costs are removed from the panel bill of materials (BOM). A central goal of this study was to quantify these cost variations in high-volume production over time. Weighing the cost analysis with the other COE and CPOL trade-offs was used as the rationale to create a COE adoption forecast.

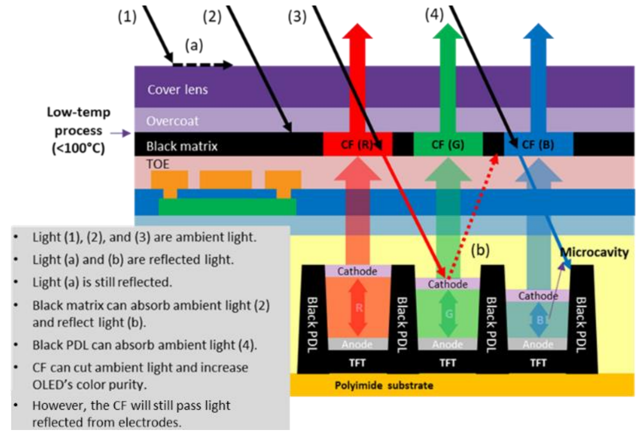


**Figure 1. COE cross-section illustrating reflection patterns**

## 2. Methodology

COE's thinness and flexibility will likely drive rapid and high adoption rates in foldable OLED display applications. In the case of conventional, flat bar-type smartphones COE's advantages are less obvious and its cost differential with CPOL becomes a more important determining factor.

In this study, the total manufacturing cost for a 6.1", 2556 x 1179, flexible, flat, LTPO OLED panel with C-POL was compared to a similar panel with COE. Panels with both liquid crystal (LC) and film-type polarizers were analyzed.

**Table 1. Key cost modeling parameters**

| Parameter | C-POL | COE |
|---|---|---|
| Substrate size | 1500 x 1850 mm | 1500 x 1850 mm |
| Time range | 2024-2028 | 2024-2028 |
| Fab operation | 80% | 80% |
| Capacity (TFT equivalents) | 30,000 substrates per month | 30,000 substrates per month |
| Depreciation | 5 years | 5 years |
| Capital costs | OLED factory with only C-POL lamination | OLED factory with all equipment for COE |
| Material costs | LC and film-type polarizers | Low process temperature COE photoresists, black PDL, photomasks |
| Yield curve | 68-74% over range | 76%-77% over range |

In this comparison, the key parameter that affects total manufacturing cost in conventional OLED panels is the price of the


ISSN 0097-996X/25/5601-0217-$1.00 

add-on C-POL.

This is eliminated in the case of COE. However, additional costs are incurred because a COE-capable factory necessitates the procurement of a large number of manufacturing tools specifically to coat and pattern required films. The cost of these machines and related facilities needs to be depreciated over all panels produced over a fixed time. In this analysis, a 5-year assumption was applied.

Additionally, COE films are patterned from black-matrix (BM), red, green, and blue photoresists. These materials are sequentially added to the display after evaporation of the emission layers and thus need to be cured at temperatures less than 100°C to avoid damaging the organic materials.

Furthermore, extra process steps and specialty material properties negatively affect the total yield.

Similar production time ranges, fab operation, capacity, etc. are applied to both panel types to provide a “likes” comparison, which in turn highlights cost differences driven explicitly by COE.

A wide variety of other assumptions and parameters are used to model costs. These are not discussed in detail here as they do not substantially influence the variations in the manufacturing of COE and CPOL-type OLED panels.

Price, cost, yield, and other data are regularly collected through systematic, in-person interview-type surveys of flat panel display (FPD) supply chain companies by a team of analysts based in the regions where FPDs are primarily manufactured. Survey participants include material and component makers, equipment makers, panel makers, set makers/brands, and other relevant companies.

Information gathered is data-based and checked every quarter to validate and track changes over time. These databases enable bottom-up modeling of panel costs.

This standard methodology is used to model conventional CPOL OLED panel manufacturing costs. To model COE panel costs, targeted surveys were used to confirm parameters that affect COE. These were used to adjust and expand the model to cover COE OLED panels. A second round of surveys was conducted to validate results before finalizing the conclusions reported here.

## 3. Results

### Advantages and disadvantages of COE

As shown in Tables 3 and 4, surveys confirmed a range of advantages and disadvantages of COE compared to C-POL. The most significant of these is higher ambient light reflection from metal electrodes.

Optimization is important to mitigate COE’s disadvantages. Strategies include the following:

- Adopting a black pixel definition layer (PDL)
- Minimizing pixel-to-aperture ratio
- Minimizing pixel-to-BM distance
- Increasing CF film thickness
- Maximizing anode flatness
- Adopting a circular anode/BM design
- Increasing the PDL taper angle (e.g., 30°)

Conventional PDL films are made from transparent polyimide. Black PDL films are opaque, which is why they block reflection and how they improve COE performance. However, developing an appropriate black PDL photoresist has been challenging and has taken many years of R&D. The black pigment in the resist absorbs so much light that achieving the required PDL profiles by photolithography has been difficult. Now, with multiple makers recently introducing new, higher-performance black PDL materials to the market, the trade-offs between C-POL and COE are diminishing.

**Table 2. Advantages of COE compared to C-POL**

| Detail | Comments |
|---|---|
| Increased brightness | Considerable range in reported numbers, 20-25%, key advantage. |
| Reduced power consumption & longer lifetime | Linked to brightness increase, considerable range in reported numbers. Important COE benefit. |
| Easier process for rounded areas | Reduce OCA and PSA, film stress, and delamination risk. |
| Thinner than polarizer | About a 30% reduction compared to C-POL (360 > 250 μm). |
| Reliability | Reduce film stress and delamination risks; increase the number of times the display can be bent. |
| Wider color gamut | > +20% |
| Reduced bending radius | For foldable apps, due to thinner film; for example, 1 mm. |
| "Sunglasses-Free" | Compatible with polarized sunglasses without extra COP film. |

**Table 3. Disadvantages of COE compared to C-POL**

| Detail | Comments |
|---|---|
| Increased ambient light reflection in a diffraction pattern. | For example, 5-7%. A considerable range in reported numbers. Can be reduced by COE pixel design optimization, black PDL, etc. |
| Photomasks | Additional cost, particularly for low volume orders and R&D. Additional TFT mask step as half-tone black PDL difficult. |
| Additional process steps, more equipment, larger fab | Adds to fab depreciation and running costs. Adds cost, but not necessarily more than CPOL. |
| Yield loss | COE process yield assumed 90-95% already. However, black PDL yield is still challenging, varying by material and maker. |
| Inoperability concerns with optical fingerprint sensors | Shift to ultrasonic FoD sensor but may add further cost. |
| Unattractive dark mode appearance | Consumers find high reflectance and color deviation annoying, even when the display is off. |

### Cost comparison of COE to C-POL

Detailed surveys of OLED supply chain companies, panel makers, and brands are useful research techniques to generate qualitative lists and results. In this case, however, surveys only returned general comments on the relative cost of COE to C-POL. No publicly available cost analysis could be found. Interviewees –who were all display industry professionals– generally just assumed COE is expensive because of the high upfront costs of the additional photolithography and supporting equipment. However, they were not able to back up their assumptions. This lack of data was the primary motivator for this study.

At the same time, specific data, such as number and type of machines required, machine capacity and price, C-POL prices, number of photomasks and prices, low-temperature compatible photoresist prices, film thickness, price declines over time, yield rate assumptions, etc. were successfully gathered as part of the survey process.

Using this specific surveyed data and OMDIA cost models, the results in Tables 4 and 5 were calculated and validated.

Actual costs will vary considerably by panel maker and manufacturing specifics, depreciation accounting practices, factory operation, yield rates, etc.

Specialty black PDL and low-temperature compatible color resists are substantially more expensive than their conventional counterparts due to lack of maturity, still low volume consumption, and the amount of R&D required to bring the materials to current performance levels.

Even so, materials costs are minimal compared to COE equipment depreciation. At Gen 6, machines required to add 30,000 substrates per month of COE capability can easily exceed $100 million and in some cases significantly more. However, as these costs are depreciated over every panel produced over at least a 5-year period, the depreciated costs per panel are relatively small and only account for a couple of percent of the panel's total manufacturing cost.

Surveys suggested the yield rates for the color filter (CF) part of the process are already high and patterning it may only be moderately more difficult than conventional CF. At the same time, the adoption of black PDL will harm yield as it is more difficult to pattern than conventional transparent PDL materials.

**Table 4. Manufacturing costs of a 6.1-inch 2556 x 1179 flexible flat LTPO OLED with COE**

| Category | Subtotals, etc. | Details | 2024 | 2026 | 2028 |
|---|---|---|---|---|---|
| | Yielded Array Material Cost | | $0.44 | $0.38 | $0.35 |
| | Yielded OLED Color patterning Material Co: | | $2.12 | $1.79 | $1.53 |
| | | COE material | $0.18 | $0.16 | $0.16 |
| | Yielded Encap & COE Material Cost | | $0.31 | $0.27 | $0.26 |
| | | C-POL | | | |
| | Yielded Module Component Total | | $15.80 | $13.83 | $12.12 |
| Yielded Material and Component Total Cost | | | $18.67 | $16.28 | $14.27 |
| Labor Cost | | | $2.98 | $3.27 | $3.60 |
| | 5 Year Straight Line Dpreciation (COE) | | $0.58 | $0.56 | $0.54 |
| Depreciation Cost | | | $9.55 | $9.14 | $8.86 |
| Indirect Expense Total | | | $2.03 | $1.79 | $1.58 |
| Manufacturing Total Cost | | | $33.24 | $30.48 | $28.30 |
| Total Yield | | | 68.2% | 71.5% | 74.1% |

At the same time, C-POL are expensive films. Panel makers buy polarizing films from specialty makers and laminate them to completed panels. C-POL prices vary by their type and quality.

LC-type CPOL provide the best performance but are also the most expensive type commonly used in OLED display applications. LC-CPOL are now being adopted for both foldable phones and high-end bar-type phones.

**Table 5. Manufacturing costs of a 6.1-inch 2556 x 1179 flexible flat LTPO OLED with LC-type C-POL**

| Category | Subtotals, etc. | Details | 2024 | 2026 | 2028 |
|---|---|---|---|---|---|
| | Yielded Array Material Cost | | $0.40 | $0.36 | $0.34 |
| | Yielded OLED Color patterning Material Cost | | $1.91 | $1.67 | $1.47 |
| | | COE materials | | | |
| | Yielded Encap & COE Material Cost | | $0.05 | $0.05 | $0.04 |
| | | Circular polarizer | $1.12 | $1.03 | $0.95 |
| | Yielded Module Component Total | | $17.00 | $14.95 | $13.15 |
| Yielded Material and Component Total Cost | | | $19.36 | $17.02 | $15.00 |
| Labor Cost | | | $2.88 | $3.16 | $3.47 |
| | 5 Year Straight Line Dpreciation (COE) | | | | |
| Depreciation Cost | | | $8.09 | $7.96 | $7.93 |
| Indirect Expense Total | | | $1.94 | $1.70 | $1.50 |
| Manufacturing Total Cost | | | $32.26 | $29.83 | $27.91 |
| Total Yield | | | 75.8% | 77.0% | 77.3% |

The modeled cost variance between OLED panels with COE compared to LC-Type CPOL turns out to be only 3% in 2024 and declines to 1.5% in 2028. Considering the margin of error in survey-based cost modeling, this variance is minor.

For lower-priced film-type CPOL, the modeled cost difference is about 2X that of LC-type CPOL.

## 4. Conclusion

COE is rapidly becoming the predominant anti-reflection technology applied to foldable OLED smartphones. In addition to its flexibility, COE offers a variety of other advantages that are also useful in flat, bar-type smartphones.

To what degree the enormous bar-type smartphone market will adopt COE is currently a key question for display supply chain companies.

This study concludes that the cost variation between COE and LC-type CPOL is minor and is not likely to be the determining factor for smartphone brands when deciding which anti-reflection technology to adopt.

This implies that the decision to adopt COE in bar-type smartphone applications will be driven by its perceived image quality advantages and disadvantages compared to CPOL.

Currently, the adoption of COE in bar-type phones is negligible, likely due to not fully resolved glare issues. Over time, further optimization of the COE process will improve optical performance, and many brands are interested in adopting COE if it can satisfy target specifications.

Omdia currently forecasts that COE penetration in foldable phones will increase from about 50% in 2024 to almost 90% in 2030. For bar-type phones, COE penetration will increase from almost zero in 2024 to almost 20% in 2030. With the conventional bar-type market so much larger than the foldable market, COE in bar-type smartphones will overtake COE in foldable applications by 2030.

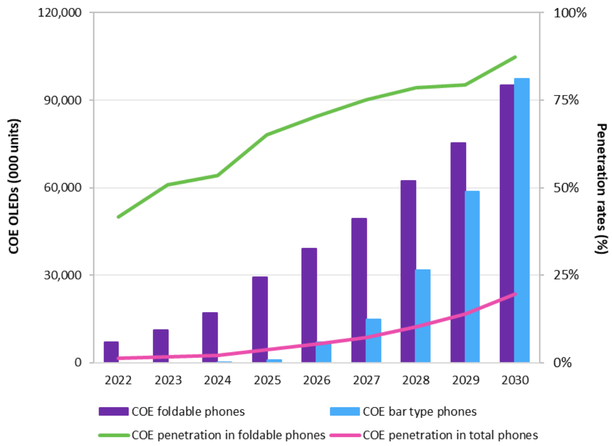


**Figure 2. COE adoption in OLED smartphone panels**

## 5. References

[1] Xu C, Shu X, Yao Q, Yuan G, Wu H, Sun S, et al. FLI Structure for R1 Foldable AMOLED Display. BOE Technology Group Co., Ltd. SID 2020 Digest; 1811-1814.

[2] Xue H, Li H, Zhou M, Dang P, Shen Y, Zhu X. Study of the Reflected Diffraction of COE. Hefei Visionox Technology Co., Ltd. Kunshan Govisionox Optoelectronics Co., Ltd. International Conference on Display Technology 2024 (Volume 55, Issue S1); 964-967.

[3] Xu C, Shu S, Lu J, Yuan G, Yao Q, Wang L, et al. Foldable AMOLED Display Utilizing Novel COE Structure. BOE Technology Group Co., Ltd. SID 2018 Digest; 310-313.

[4] Park R. Display Long-Term Demand Forecast Tracker. Omdia. October 2024.

[5] Kim J, Uno T, Heo I. OLED Display Cost Model. Omdia. May 2024.